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Washing of Illinois Coals

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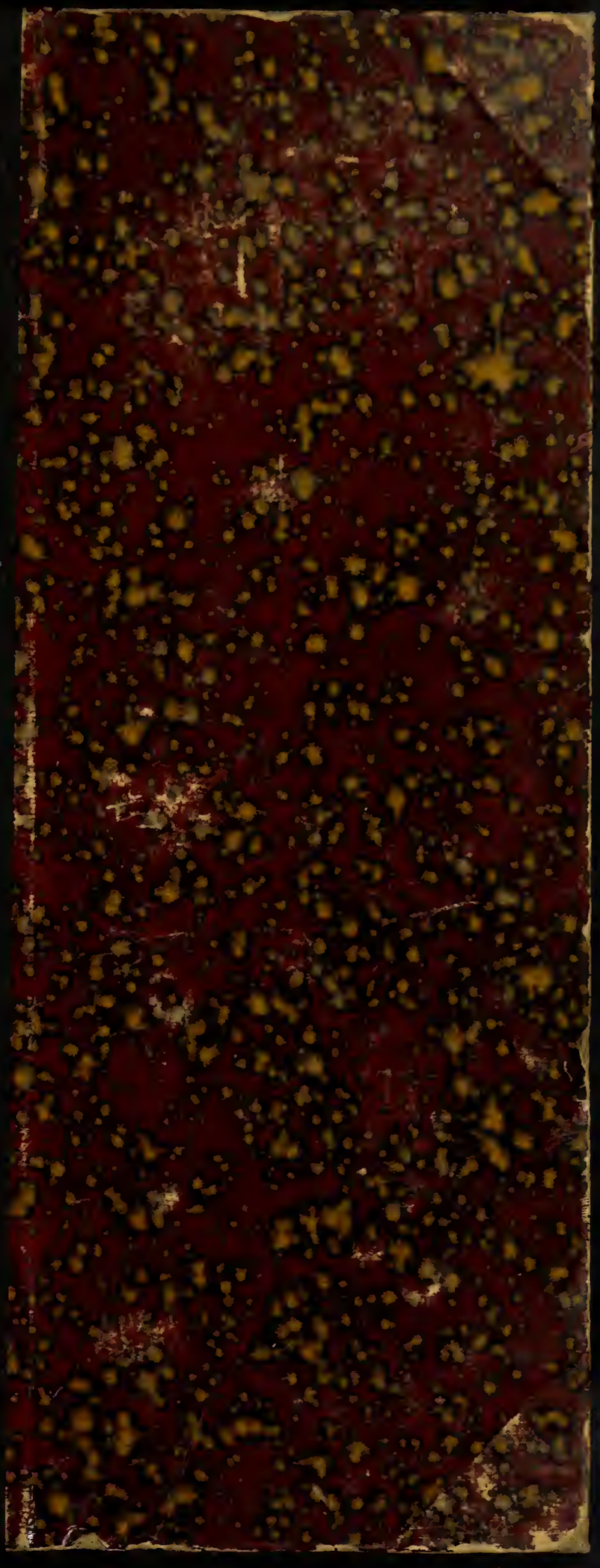

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THE WASHING

OF

ILLINOIS COALS

BY

ERNEST JEROME ROSSBACH

THESIS

FOR THE

DEGREE OF BACHELOR OF SCIENCE

IN

MINING ENGINEERING

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THE WASHING OF ILLINOIS COALS.

TABLE OF CONTENTS.

	Page.
INTRODUCTION	2
GENERAL THEORY	3
SCOPE OF THE THESIS	9
FREE SETTLING RATIO	
A. IN STILL WATER	
a. Theory	11
b. Apparatus and Instruments	11
c. Manipulations	12
d. Results	13
e. Discussion and Conclusions	14
B. AGAINST RISING CURRENT	
a. Theory	17
b. Apparatus and Instruments	20
c. Manipulations	20
d. Results	21
e. Discussion and Conclusions	21
HINDERED SETTLING RATIO	
a. Theory	23
b. Apparatus and Instruments	25
c. Manipulations	25
d. Results	25
e. Discussion and Conclusions	25
CONCLUSIONS	27

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INTRODUCTION.

Coal washing is the partial separation by use of water of more or less pure coal from the associated impurities. This separation is advantageous in that the sulphur and ash contents of the coal are reduced and thus the fuel is improved in quality or made fit for the manufacture of coke. During recent years, the importance of the coal washing industry has been growing rapidly as is evidenced by the increased tonnage of coal washed in the United States per year. In 1907 this amounted to 12,981,514 tons. In 1908 to 13,660,478 tons, and in 1909 to 16,541,874 tons. (Coal Reports of E. W. Parker for 1907, 1908, and 1909). The major portion of these tonnages was washed in preparation for the coke ovens but the writer is convinced that it will not be long before the domestic washed coal will exceed in tonnage that washed for the manufacture of coke. All of the coal washed in Illinois is for domestic consumption; consequently any increase in the state's output of washed coal indicates an increased demand for this commodity. Referring again to the coal reports, we learn that in 1907 2,988,386 tons of coal were washed in the state, which figure increased to 3,768,112 in 1908 and to 4,064,085 in 1909. This represents an increase of 36 per cent in two years. Several prominent Chicago wholesale coal dealers have informed the writer that domestic washed coal already finds a ready market there.

However well the industry is developed commercially, it is not yet firmly grounded scientifically. This is seen in the wonderful claims made by the manufacturers of washers for their own type of machine. Each admits that his installation is the panacea for

all ills to which coal and coal markets are subject. Very little attention has been paid to the scientific investigation of coal washing problems, which is markedly in contrast to the practice in ore dressing which is completely analogous to coal washing. This is largely due to the cheapness of the material handled and to the consequent importance of quantity rather than quality.

It was with the hope of learning something concerning two fundamental relations of importance in bituminous coal washing that this thesis was undertaken.

THEORY.

The impurities associated with bituminous coal are of two varieties: 1. Those which are an intimate component part of the coal. 2. Those which do not enter into its constitution. The second class of impurities can be mechanically separated, the first cannot. Shale, pyrite, fireclay, and gypsum comprise the separable class. The average specific gravities of these are:

Shale	2.6
Gypsum	2.32
Fireclay	2.6
Pyrite	4.9

Gypsum seems to present the greatest difficulty with its specific gravity of 2.32. This substance, however, is of little importance because it occurs in inconsiderable amounts although it is a very common impurity.

Next to the gypsum rank fireclay and shale, the specific gravities of which are 2.6. Fireclay is not of importance in

washing because it is the duty of the miner to load "clean coal", which requirement results in this impurity being picked from the coal before or while loading. Shale is an omnipresent impurity in the case of bituminous coals, and in point of difficulty of separation is far and away the most troublesome one. The reason for this is that pure shale often grades, one might even say shades, into an impure coal called "bone". This property may result in a series ranging from "clean coal" through "bone coal", and carbonaceous shale to pure shale, said series ranging in specific gravity from that of the first substance to that of the last without any discontinuities. It is obvious that the washing of a coal consisting of such a series presents obstacles which are well-nigh insurmountable by means which are of economic importance.

The pyrite, except when it is very finely divided and disseminated throughout the coal, presents no difficulties because of its high specific gravity. Even when it is in a state of fine division and disseminated throughout the coal it is only necessary to crush the coal to a fine size, and to refrain from reusing the wash water. From the foregoing it is evident that, in general, if a coal be so washed as to separate out the shale, the other impurities will take care of themselves. For this reason the present investigation was confined to a study of the settling properties of "clean coal" and shale.

The separation of materials of different specific gravities by washing or classifying as it is known in the case of ores, is dependent upon the properties of mineral substances settling in fluids. The rate with which a given particle will settle through a fluid is dependent upon: First, its specific

gravity, second its size and shape, third the specific gravity of the fluid and of lesser importance, fourth, air bubbles adhering to the particles. For example, suppose a number of particles of different minerals which vary as to size and shape to be dropped in a tank of water. Those particles of the highest specific gravity will tend to reach the bottom of the tank first, but relative sizes and shapes may prevent this, thus causing several particles of different composition and specific gravity to fall together. Suppose, now, that all of the particles are of a uniform size and shape. In this case the heavier particles will settle most rapidly and thus be separated from the lighter ones which will come to rest on the former. This process is somewhat similar to what in Nature is called stratification. It is by use of this phenomenon that coal and ores are freed from impurities or gangue material. The shapes of the particles of the same specific gravity and size cause them to settle with different velocities. It has been found that rounded grains fall faster than long thin grains of the same size, although these in turn outstrip flat grains which remain upon the same screen. The specific gravity of the fluid through which the particle settles also exercises an influence upon its velocity of descent, for the greater the specific gravity of the medium, the greater its bouyancy. Last, and, in truth, least, the adherence of air bubbles to the descending particle tends to slow it somewhat. This factor is of inconsiderable importance in coal washing because of the large size of particles although it plays an important part in ore concentration. The relation between the settling velocity and the size and specific gravity of the particle together with the

specific gravity of the settling medium is merely a matter of applied mechanics.

The particle is acted upon by three forces: I. That of gravity in a downward direction. 2. The upward bouyant force of the fluid, and 3, the resistance which the fluid opposes to the downward passage of the particle. The first is, of course, independent of all considerations, producing an acceleration of 32.2 feet per second per second in vacuo. A fluid's bouyant effect upon a particle is, as all of us have learned from Archimedes' experiment, due to a force equal to the weight of the vdume of the fluid displaced by the particle. Expressing this as a formula:

$$F_b = sw \frac{\pi}{6} \cdot D^3$$

where D is the diameter of the particle which is assumed, for simplicity, to be spherical; s is the specific gravity of the fluid; andw is the weight of unit volume of water.

Since the force of gravity which produces the downward acceleration is equal to the weight of the particle accelerated, this is :

$$F_g = Sw \frac{\pi}{6} \cdot D^3 \quad \text{in vacuo,}$$

where S is the specific gravity of the particle. Now when the particle is immersed in the fluid its active or "available" weight is:

$$F_g - F_b = Sw \frac{\pi}{6} D^3 - sw \frac{\pi}{6} D^3$$
$$= \frac{\pi}{6} D^3 w(S-s)$$

This force is in a downward direction.

Neglecting viscosity which is only of relative importance in the case of low velocities, the third force, that due to the resistance of the fluid to the downward passage of the particle, varies partly with the square and partly with the first power of the velocity. However, the resistance may safely be considered as varying only with the square of the velocity when this is considerable. The resistance is almost universally given by the authorities as equal to:

$$K\ A\ ws\ \frac{v^2}{2g} = F_r,$$

where A is the cross-sectional area opposed to motion, and K is a constant which varies with the shape of the particle.

Adopting 0.5 (Henry Louis)* as the value for K in the case of the spherical particle under consideration, the resistance becomes:

$$F = 0.5\ (\pi\frac{D^2}{4})\cdot(\frac{v^2}{2g})\cdot ws,$$

where v is the velocity of the inches per second, and g is the acceleration of gravity in inches per second per second.

It is apparent that when the weight causing acceleration is just equal to the resistance of the fluid the forces will be in equilibrium and there will be no further acceleration. In other words the velocity becomes constant under this condition. Equating therefore:

$$0.5\ (\pi\frac{D^2}{4})\ (\frac{v^2}{2g})\ ws = \frac{\pi}{6}D^3w(S-s)$$

$$\frac{v^2}{1029.33} = D\ (\frac{S-s}{s})$$

*. "The Dressing of Minerals"

$$v^2 = 1029.33 \cdot D\left(\frac{S-s}{s}\right)$$

$$v = 32.08 \sqrt{D\left(\frac{S-s}{s}\right)} \text{ inches per second per sec.}$$

Had the particle under consideration been a cube of side L inches, the formula would have been derived as follows:

$$F_g - F_b = L^3 w (S-s)$$

$$F_r = KL^2 ws \left(\frac{v^2}{2g}\right)$$

$$= 1.28 L^2 ws \left(\frac{v^2}{2g}\right), \text{ using } K = 1.28 \text{ (Henry Louis.}$$

Equating:

$$L^3 w (S-s) = 1.28 L^2 ws \left(\frac{v^2}{2g}\right)$$

$$\frac{1.28 v^2}{2g} = L \left(\frac{S-s}{s}\right)$$

$$\frac{0.64 v^2}{386} = L \left(\frac{S-s}{s}\right)$$

$$v^2 = 603.12 L \left(\frac{S-s}{s}\right)$$

$$v = \sqrt{603.12} \sqrt{L \left(\frac{S-s}{s}\right)}$$

$$= 24.56 \sqrt{L \left(\frac{S-s}{s}\right)} \text{ in. per sec.}$$

If the falling particle be of irregular shape, that is other than spherical or cubical, it has been customary to treat is as a cube whose diameter is such that the sphere's volume is just equal to that of the irregular particle. However, this need be considered no further in this thesis.

This discussion of the theory of mineral particles settling in a fluid is pratically the same as that of Henry Louis in his

work on the dressing of *minerals. (referred to above).*

The above clearly shows that there is a definite relation between the sizes of particles of two minerals of different specific gravity which will have the same velocity of descent in the same fluid. This ratio is easily obtained from the above formulae:

$$V_1 = K\sqrt{D_1\left(\frac{S-s}{s}\right)}$$

$$V_2 = K\sqrt{D_2\left(\frac{S_2-s}{s}\right)}$$

$$V_1 = V_2 = K\sqrt{D_1\left(\frac{S_1-s}{s}\right)} = K\sqrt{D_2\left(\frac{S_2-s}{s}\right)}$$

$$K\sqrt{D_1\left(\frac{S_1-s}{s}\right)} = K\sqrt{D_2\left(\frac{S_2-s}{s}\right)}$$

$$\frac{\sqrt{D_1}}{\sqrt{D_2}} = \frac{\sqrt{\frac{S_2-s}{s}}}{\sqrt{\frac{S_1-s}{s}}}$$

$$\frac{D_1}{D_2} = \frac{\frac{S_2-s}{s}}{\frac{S_1-s}{s}}$$

It is obvious that this ratio is indepedent of the shapes of the particles provided that the particles all have the same shape.

SCOPE.

The task which the writer set for himself in this thesis was the ascertaining, experimentally, of the relation between the sizes of particles of shale and of a bituminous coal which are

possessed of equal settling velocities in water. The reason for confining the investigation to one bituminous coal was a lack of sufficient time to accomplish more. However the investigation has for its goal two ratios, not one. This is due to the fact that two conditions under which a particle may settle in a fluid exist. The particles may settle through the fluid (water in this case) unhindered, or they may settle through the fluid which has become a sort of quicksand by having particles of a mineral in suspension just as does a "boiling" spring with a sandy mouth. The first case is that of "free-settling", the second that of "hindered-settling". In the former the fluid has a specific gravity equal to that of the liquid; in the latter the fluid specific gravity is that of the "quicksand". By a recollection of the foregoing formulas it is clear that these two conditions will yield differing "free-settling" and "hindered-settling" ratios.

Specifically, then, the scope of this thesis is the experimental determination of the "free-settling" and "hindered-settling" ratios of coal and shale from the rib of the 13th South Entry off the Main West Entry of the Electric Coal Mine at Hillery, Illinois.

The value of such an investigation as this lies partly in the incidental testing of the theory involved, but mostly in the information derived therefrom concerning the closeness with which the minerals studied must be sized before washing or concentrating to obtain the best results.

FREE SETTLING RATIO.

A. In Still Water.

THEORY. The theoretical free settling ratio between the coal and shale of this investigation is:

$$\frac{D_1}{D_2} = \frac{\frac{S_2 - S}{S}}{\frac{S_1 - S}{S}} = \frac{1.21-1}{2.58-1} = \frac{0.21}{1.58} = 0.133$$

APPARATUS, INSTRUMENTS, ETC. The coal upon which all of the investigations were made was taken from the 13th South Entry off the Main West of the Electric Mine located at Hillery, Ill. This sample was taken by the writer according to the United States Bureau of Mines rules for sampling coal, and one cut was quartered down for analysis.

The analysis*:

	As received.	Air-dried.	Moisture free.	"Unit" coal.
Moisture	13.27	1.95		
Volatile matter	40.44	45.72	46.63	
Fixed carbon	37.46	42.35	43.19	
Ash	8.83	9.98	10.18	
Sulphur	3.27	3.70	3.77	
CO_2	0.38	0.43	0.44	
B. T. U.	11209	12673	12925	14650

Twenty observations with a Jolly balance of the specific gravity of the clean coal yielded an average of 1.21. The greatest var-

*Made by the University of Illinois' fuel laboratory.

iation from this average noticed was 0.006.

The shale used throughout this work was taken from the same rib as was the coal. Its specific gravity is on the average, 2.58. The greatest variation from this figure has been 0.04.

The free-settling tests were all conducted with a soft glass tube which is 2 11-32" in inside diameter and about 5 feet in length. This tube was supported in a vertical position by a large ring-stand equipped with cork-lined grips, the lower end of the tube having been sealed by a rubber stopper reinforced with sealing wax and copper-wire. To reduce to a minimum in these tests the friction against the sides of the tube, it was plumbed frequently and, if necessary, adjusted to a vertical position. Two rubber bands were placed about the tube in a horizontal plane, one near the top, the other just 48 inches below the first.

A stop-watch or timer, graduated to fifths of a second, was employed to record the time of descent of particles.

The set of sieves employed in sizing the material was of the double Rittinger ($\sqrt[4]{2}$) scale, or rather the closest to this scale which can be secured on the market. It included all sizes from 0.00286 to 0.505 inch mesh.

MANIPULATIONS. The method of making the free-settling tests was as follows: First, the size of coal or shale required for the prospective experiment was prepared. This was done in the case of the large particles by cutting them to size with a pair of mineralogical nippers, and in the case of the smaller particles, by screening out the desired size. In either case, the effort was to secure cubical particles, which was accomplished by selection when possible and otherwise by trimming. Next, the tube was plumbed, adjusted, if

necessary, and filled with water, to a point near its mouth. Then, having adjusted the length of the interval between the rubber bands, the timing of the descent of the particles under consideration from the plane of the upper band to that of the lower was begun. When fairly large particles were being timed, they were dropped one by one and timed individually; when smaller particles were being investigated, about fifty grains were dropped together, and the fastest of these were timed. At least twenty trials were made upon each size of each material. The average time of descent was computed for each size and divided into forty-eight, which operations yielded the average settling velocities in inches per second. These were tabulated and plotted. Finally the equal settling ratios were computed (by means of the experimental curves) for a number of velocities. The results:

AVERAGE VELOCITIES FOR COAL.

Size in inches:	0.8	0.7	0.6	0.5	0.420	0.352	0.298	0.251	0.209
Average velocity in secs.	7.86	6.85	6.16	5.85	5.30	4.62	4.00	3.72	3.19

Size in inches	0.178	0.150	0.126	0.104	0.089	0.0445	0.0265	0.011
Average velocity in secs.	2.91	2.62	2.23	2.10	1.68	1.18	0.783	0.38

See Curve Sheet 1.

AVERAGE VELOCITIES FOR SHALE.

Size in inches:	0.126	0.104	0.089	0.0445	0.0265	0.011
Average velocity in. per sec.	8.58	7.25	6.76	4.30	3.21	1.33

See Curve Sheet 2.

FREE SETTLING RATIO.

Velocity in.per sec	0.5	1.0.	1.5	2.0	2.5	3.0	4.0	5.0	6.0	7.0
Size coal in.	.0145	.0348	.063	.096	.136	.183	.29	0.4	.535	0.69
Size shale in.	.003	.0067	.0103	.0147	.0192	.0242	.0382	.057	.0758	0.0951
Ratio	.207	.193	.164	.153	.140	.1323	.1316	.1425	.1419	0.138

See Curve Sheet 3

DISCUSSION AND CONCLUSIONS. These results depart from the theoretical values as may clearly be seen by a glance at curve sheets, 1 and 2. The curves show the experimental and theoretical relations between size of particles and velocity of descent (1) for coal and (2) for shale. In each case, the experimental curve seems to have the same general shape as the theoretical one but lies nearer the ordinate axis, that is to say, the velocities actually attained are not so great as the theory would indicate. Professor Richards of the Massachusetts Institute of Technology secured analogous results with anthracite, these being given out by him in his address before the Pittsburg meeting of the American Institute of Mining Engineers in March, 1910. I have plotted his results on curve sheet 5. The marked similarity of relations between experimental and theoretical curves on sheets 1, 2, and 5 is at once ap-

parent.

Despite appearances the experimental curves are not truly parabolic as are the theoretical ones, whose equation as given above, is $V = K\sqrt{L\,\frac{S-s}{s}}$. With any given mineral, $(\frac{S-s}{s})$ becomes a constant. Therefore the theoretical curve may be said to have an equation:

$$V = K\sqrt{L}$$

The experimental curve must have the general equation:

$$V = K\,L^{x}$$

where K is some constant.

But this equation contains two variables and does not lend itself to simple solution. However by having recourse to logarithms, it becomes

$$\log.\ V = \log.\ K + x \log L.$$

Now when L = 1, log. L = 0 and x log L is also zero. Therefore, for L = 1,

$$\log.\ V = \log.\ K.$$

and $$V = K.$$

By referring to the exterpolation curve on curve sheet four, it is seen that V = 8.6 when L = 1. Thus the value 8.6 is obtained for K. The exponent x may now be evaluated by means of the equation:

$$\log.\ V - \log.\ K = x \log.\ L.$$

This has been done for all sizes of coal between the limits, L = 0.3 and L = 3.104.

The results:

L	0.8	0.7	0.6	0.5	0.42	0.352	0.298	0.251	0.209	0.178
x	0.403	0.638	0.648	0.557	0.557	0.595	0.631	0.651	0.634	0.628

L	0.15	0.126	0.104
x	0.627	0.651	0.624

The average of these values of x is 0.6034. Omitting the first value, (0.403) which is obviously in error (see curve sheet 1) the average is 0.620, which is perhaps more representative. The reason for the inconsistent value for 0.8 inch coal is doubtless that this size is too large for the tube used. The data for coal under 0.104 inch was not considered in this connection, because viscosity produces a change in the slope of the curve. Reference to curve sheet one will verify this statement. The curve for the larger sizes of coal, then, has the formula:

$$V = 8.6\ L^{0.8200}$$

For shale the computations are similar.

Results:

L	0.126	0.104	0.089	0.0445
x	0.414	0.453	0.449	0.495

These values average 0.453, in consequence of which the formula must be:

$$V = 20.2\ L^{0.453}$$

The average experimental value of the free-settling ratio

was, as we have seen, 0.154. This is somewhat in excess of the theoretical value of 0.133. However, there would be a closer agreement were the smaller sizes of coal and shale to be neglected. Casting out the first two ratios in the table, the average ratio becomes 0.1429 which is, perhaps, more truly representative.

Since coal up to 3 inches in size is washed for domestic use, it is interesting to know what the ratio becomes for larger sizes than those represented in the writer's experiments, which were limited in range by the size of tubing available. For this reason the experimental curves were continued beyond the upper limit of the data. These interpolation curves are presented on curve sheet 4. The ratios obtained by use of these curves are:

Velocity	8.0	10.0	12.0	14.0
Coal	0.866	1.337	1.93	2.84
Shale	0.1146	0.176	0.2865	0.396
Ratio	0.132	0.132	0.139	0.1394

Including these four values in the data, the ratio becomes 0.149. Again excluding the first two values, it is reduced to 0.140. Too much reliance must not be placed in the accuracy of the exterpolations, of course. Yet, the curves, being regular, admit of fairly accurate extension.

Against Rising Current.

THEORY. Rittinger, the pioneer investigator of the subject of wet classification, assumed that the theoretical considerations in the case of a particle settling against a rising cur-

rent of water are the same as in the case of still water. Subsequent investigators, have, as a rule, taken this assumption as correct. However, Rankine, according to Henry Louis, (I have failed to find the reference) maintained that this was in error and later F.M.F.Cazin (Trans.A.I.M.E.) Bridgeport Meeting, Oct. 1894) declared the assumption not justified. Yet, Professor Richards has obtained the same ratio, experimentally, for both cases. Let us examine the question from the standpoint of mechanics.

The mineral particle is acted upon by four forces, viz: (1) gravity - (Fg) - downward; (2) bouyancy -(Fb) - upward; (3) "frictional" resistance of the water to downward passage of the particle - (F_r) - upward, and (4) the force of the rising current - (F_c) - upward. From the general theory we know that the resultant of (1) and (2) is

$$F_g - F_b = \frac{\pi}{6}(S-s)\, D^3\, w, \text{ which is downward.}$$

Likewise:

$$F_r = 0.5 \left(\frac{\pi}{4} D^2\right) \frac{v^2}{2g} \quad \text{(The particle being spherical).}$$

Now, since $F_c = M_p a_p$:-

m_p = mass of particle
a_p = acceleration which F_c tends to produce with particle.

$$F_c = \frac{\left[\left(\frac{\pi}{6} D^3\right) S w\right] a}{g}$$

From this we see that the total upward force is:-

$$\frac{\pi D^3\, S\, w\, a}{6g} + 0.5 \cdot \frac{\pi\, D^2\, v^2}{8g}, \quad \text{or simplified:}$$

$$\frac{4\pi D^3\, S\, w\, a + 1.5\pi D^2\, v^2}{24\, g}$$

When the upward and downward forces are in equilibirum, the parti-

cle is either at rest or in a state of uniform motion.

Equating therefore:

$$\frac{\pi}{6}(S-s)\,D^3\,w = \frac{\pi D^2\,(4\,S\,w\,a\,D + 1.5v^2)}{24g}$$

$$(S-s)\,D\,w = \frac{4\,S\,w\,a\,D + 1.5\,v^2}{4g}$$

$$4g\,(S-s)Dw = 4\,S\,w\,a\,D + 1.5v^2$$

$$4g\,(S-s)Dw - 4S\,w\,a\,D = 1.5v^2$$

$$v^2 = \frac{4}{1.5}\,w\,D\,(g\,(S-s) - Sa)$$

$$v = \sqrt{\frac{4}{1.5}}\ \sqrt{w\,D\,(g\,(S-s) - Sa)}$$

For a cube, this becomes

$$V = \sqrt{\frac{4}{3.84}}\ \sqrt{w\,D\,(g\,(S-s) - Sa)}$$

To obtain the ratio:-

$$\sqrt{\frac{4}{15}}\ \sqrt{w\,D_1\,(g\,(S_1-s) - S_1a_1)} = \sqrt{\frac{4}{15}}\ \sqrt{w\,D_2\,(g\,(S_2-s) - S_2a_2}.$$

N.B. That (a) is not equal to a_2, although the accelerating forces are equal is obvious from the relation F=ma

$$\frac{D_1}{D_2} = \frac{g\,(S_2-s) - S_2a_2}{g\,(S_1-s) - S_1a_1}$$

This equation does not lend itself to solution without a knowledge of the values of a_1 and a_2. These values in turn can be arrived at only by a knowledge of F, the accelerating force of the ascending current. Because of the limited time at the disposal of the writer, he was unable to study the forces of the rising currents which he employed.

The equal-rising ratio is arrived at by changing the direction of the force with which the water resists the passage of the particles. This ratio is given by:

$$\frac{D_1}{D_2} \qquad \frac{S_2a_2 - (S_2-s)\,g}{S_1a_1 - (S_1-s)\,g}$$

The writer hopes by these formulae to show that the cases of settling in a still fluid and against a rising current are not alike from the standpoint of theoretical mechanics. He very much deprecates his inability to compute a value for the coal and shale of his experiments. It appears to be a subject worthy of further study.

APPARATUS. A 3-inch, one-compartment, Richards' pulsator jig and classifier were employed in making these tests. (See illustration on next page).

MANIPULATIONS. First coal and shale were sized as in the previous tests. Next either the jig or classifier was set into operation with a brisk rising current. Then coal was fed in successive sizes beginning with the smaller sizes, until it had been ascertained what size was just carried over into the overflow. Finally shale was fed in the same manner as the coal had been, until the size just passing into the overflow had been determined.

RICHARDS' PULSATOR CLASSIFIER

These two observed sizes constituted the desired ratio. To approximate working conditions, these tests were repeated with thin beds of coal and shale upon the screen of the jig.

RESULTS. The classifier yielded an average ratio of 0.200, 0.00411 inch shale being equal falling with 0.206 inch coal.

The jig with no bed upon the screen indicated a ratio of 0.211, 0.0376 inch shale corresponding to 0.178 inch coal.

When the jig was run with thin beds of coal (different sizes were tried) upon its screen, the ratio again averaged 0.211, the same sizes of shale and coal as before corresponding to one another.

Shale beds on the screen also failed to alter the ratio to any considerable extent, the ratio under these conditions being 0.213, 0.0222 and shale being equal to 0.104 inch coal.

DISCUSSION AND CONCLUSIONS. The results obtained are in not in accord with Professor Richard's observations on galena and quartz as given in the paper before the A.I.M.E. already referred to. Ih his work with these minerals he secured the same ratio for both cases of free-settling.

There are two possible explanations. First, that a different law is followed by substances of relatively low specific gravity; and second, the tendency of the shale to dissolve and break up in the water, resulting in the greatest of difficulty in determining the size of shale which just comes over into the overflow, vitiates the results.

The first explanation seeks to justify these, the second to discount them. The formulae, developed under Theory may, when

it is possible to evaluate them, prove the ratio obtained to be justifiable. It would assuredly be worth while to know that the rising current is less efficient than is the body of still water as a classifier. Further investigation may disclose the fact, if it be a fact, that the action of water on shale accounts for the recorded results.

That the thin beds of coal and shale failed to vary the ratio is interesting inasmuch as many jigs [redacted] work under just such conditions. Manufacturers of these machines have claimed that they operated under hindered-settling conditions.

HINDERED-SETTLING RATIO.

THEORY. The theory of hindered settling is not agreed upon by authorities in this field. Henry Louis advances one hypothesis and Professor Richards subscribes to another. Each of these will be considered briefly.

Professor Louis' hypothesis is quoted from his "The Dressing of Minerals":-

"Assuming two equal-falling particles of different specific gravity to be placed upon a screen, the mesh of which is smaller than the diameters of the particles, and, further, allowing these particles to be subjected to an upward moving current of water, the velocity of which is superior to the ultimate falling velocities of the particles, it is evident that both particles will be lifted. It has already been shown that under these conditions, both particles will ultimately attain the same ascending velocity, but that at the outset the specifically lighter of the two particles will be lifted the faster. If the current is interrupted and reversed before the regime of equal velocities is established, the former particle will be above the latter. If these same two particles are submitted to a descending current, the specifically heavier particle will commence to fall the more rapidly. Hence the action of the descending water current will reinforce that of the ascending current provided that the action of each is continued only for a brief time. If instead of only two particles a large number of particles of both kinds were placed upon the screen and submitted to similar water currents, the

final result would obviously be to produce two layers, a lower layer of the specifically heavier and an upper layer of the specically lighter particles. This action would be further intensified by the fact that the heavier particles being the smaller of the two can slip through interstices between the particles through which the specifically lighter could not pass, and are thus able to descend with greater ease and so to reach the bottom even more rapidly than is due to their higher falling velocities. These considerations explain the well-known fact that in practice it is easy to separate equal falling particles by jigging, and that successful jigging can be done on particles of different sizes, when the proportion of the largest to the smallest exceeds greatly the sieve ratio that would be deduced from the laws of equal falling, and affords a typical example of the effects due to hindered falling."

Professor Richards* states his hypothesis as follows:

"The cause of the difference between hindered-settling and free-settling appears to be that with free settling both quartz and galena "(which he was considering) "are settling in water with a specific gravity of 1, and they obey the laws laid down for particles settling in that liquid. With hindered-settling, however, the grains are settling in a liquid much denser than water, with perhaps 1.5 specific gravity, due to the crowding mineral grains. This, when worked out mathematically, should give a diameter ratio of 6.9 between quarts and galena, and this is exactly what has been obtained."

The writer is of the belief that Professor Richards' explanation is the more nearly correct. More will be said on this

*In the paper already referred to.

point later.

Employing the latter theory and remembering that $V = K\sqrt{D(S-1)}$ it is obvious that in the case of the coal of this investigation no particle, regardless of size, will sink in a fluid of specific gravity 1.5. Feldspar having approximately the same specific gravity as quartz will if held suspended in water by means of a rising current give approximately the same specific gravity to the resultant "quicksand". From this it would appear that the hindered settling ratio for the coal being studied is infinite when a feldspar bed is used.

APPARATUS. To test the ratio between the coal and shale of the free-settling experiments, a Richards' 3-inch, single-compartment, pulsator jig (see illustration on next page) and an ordinary piston jig, pulsion and suction being balanced, with a 6" by 4" screen compartment were employed.

MANIPULATIONS. First, cubes of coal varying in size from 0.1 inch to 1 inch were prepared. Next the jig was started and feldspar of approximately 0.1 inch size was fed until a bed was secured which was just flush with the lip of the overflow. Then the water-feed was adjusted until the bed-particles were at "full-teeter". Now the coal was fed, beginning with the 0.1 inch and ending with the 1 inch size.

RESULTS. Both the piston and the pulsator jigs discharged all of the coal particles with facility.

DISCUSSION AND CONCLUSIONS. These results bear out Professor Richard's contentions. It was impossible to test the ratio for sizes of coal in excess of 1 inch in size, because of the limited capacities of the jigs. Nevertheless, the ease with which

RICHARDS' PULSATOR JIG

the one inch pieces were handled indicated that larger sizes would meet with equal treatment. It has thus been shown that, within the limits of the present experiments, the hindered-settling ratio for the coal and shale employed is infinite.

The most striking feature in the writer's opinion of the hindered-settling tests was the action of the coal while on the feldspar bed. It was as if the coal particles had been laid upon a wooden table which was oscillating in a vertical plane, and then subjected to a horizontal force. This analogy was exactly in accord with Professor Richard's hypothesis.

CONCLUSIONS.

To seek to draw general conclusions from this work upon one bituminous coal within narrow limits would be sheer folly. The hope of the writer is that his work will be of use to some subsequent investigator as a sort of sign-post pointing the way in which he may direct his efforts to advantage.

ACKNOWLEDGEMENT.

I wish to thank Dr. Francis Church Lincoln for his assistance in the preparation of this thesis.

SIZE No.	0.8 in.	0.7 in.	0.6 in.	0.50	0.420	0.352	0.298	0.251	0.209	0.178	0.150	0.126	0.104	0.089	0.0445	0.0265	0.011	0.126	0.104	0.089	0.0445	0.265	0.011
	COAL																	SHALE					
1	6.6	6.8	7.8	8.6	8.8	10.6	12.0	12.8	15.2	16.2	17.8	22.0	23.2	28.4	40.8	61.6	126.0	5.8	6.6	7.0	11.2	14.6	36.0
2	6.0	7.2	7.8	8.0	9.0	10.2	11.8	12.8	15.4	16.6	17.8	20.4	23.0	29.0	40.4	61.4	127.0	5.6	6.8	7.0	10.8	15.2	35.0
3	6.0	7.0	7.6	8.0	9.0	10.2	12.4	13.0	14.6	16.4	19.4	21.8	22.8	28.6	39.0	61.6	129.0	5.6	6.8	7.0	11.4	15.0	36.8
4	6.4	7.2	8.2	8.2	9.0	10.4	12.0	13.0	14.6	16.4	18.2	21.8	22.6	28.4	39.8	60.8	128.6	5.6	6.4	7.0	11.4	15.4	36.0
5	6.0	6.8	7.8	8.2	9.0	10.2	12.0	13.0	14.6	16.6	18.2	21.4	22.6	28.4	41.2	60.4	124.0	5.4	6.6	7.2	10.8	14.8	35.2
6	5.8	7.0	7.8	8.2	9.2	10.6	12.0	13.2	14.8	16.6	18.2	21.4	22.8	28.8	42.0	62.0	123.2	5.6	6.8	7.0	10.8	14.8	37.0
7	6.0	7.0	7.6	8.0	9.2	10.6	12.0	13.0	15.2	16.4	18.2	21.4	22.6	28.8	41.0	62.0	127.0	5.6	6.4	7.0	11.4	14.8	36.4
8	6.0	7.0	7.8	8.2	8.8	10.4	11.8	13.0	15.4	16.4	18.4	21.8	22.8	28.8	41.0	61.4	126.4	5.6	6.6	7.4	11.0	14.8	36.0
9	6.0	6.8	7.8	8.2	9.4	10.4	12.0	13.0	15.2	16.6	18.2	21.6	22.8	28.6	41.2	60.4	121.6	6.0	6.6	7.2	11.4	14.8	36.4
10	6.2	7.2	7.8	8.0	9.0	10.4	12.0	12.6	15.0	16.2	18.4	21.2	22.8	28.6	39.8	62.2	123.0	5.6	6.6	7.2	11.4	14.6	36.0
11	6.0	7.0	7.8	8.4	9.0	10.2	11.8	12.6	15.0	16.8	18.4	21.6	22.8	28.0	40.4	61.6	129.2	5.6	6.8	7.2	11.2	14.8	38.2
12	6.0	6.8	7.8	8.2	9.0	10.4	11.8	13.1	15.0	16.4	18.4	21.8	23.2	28.2	40.6	61.2	125.0	5.6	6.2	7.0	11.0	14.8	37.0
13	6.2	7.0	8.0	8.2	9.0	10.4	12.0	12.6	15.0	16.8	18.4	21.4	23.2	28.0	40.6	62.8	121.8	5.2	6.4	7.0	11.0	14.6	35.2
14	6.2	6.8	7.8	8.2	9.4	10.4	12.0	12.8	15.0	16.8	18.2	21.4	23.0	28.6	40.6	60.6	130.0	5.2	6.8	7.0	11.0	15.6	38.8
15	6.0	7.2	7.8	8.2	9.2	10.6	12.0	12.8	15.2	16.4	18.2	21.4	22.8	28.8	41.0	61.0	129.4	5.6	6.6	7.0	10.6	15.0	38.0
16	6.6	7.2	7.6	8.0	9.0	10.4	12.4	13.0	15.2	16.8	18.4	21.6	22.8	28.4	40.2	61.6	126.0	5.4	6.6	7.4	10.8	15.2	36.6
17	6.0	7.0	7.8	8.2	9.0	10.4	12.2	13.0	15.0	16.4	18.4	21.4	22.8	28.8	40.8	61.4	128.0	5.8	6.8	7.2	11.0	14.8	36.0
18	6.0	7.0	7.8	8.2	9.0	10.6	12.0	13.0	15.4	16.6	18.2	21.6	22.4	29.2	40.2	61.4	127.6	5.8	6.6	7.0	11.2	14.8	35.2
19	6.0	7.0	7.8	8.2	9.0	10.2	11.8	12.8	15.0	16.2	18.4	21.6	22.6	29.0	40.6	61.2	126.4	6.0	6.6	7.0	11.4	14.8	36.2
20	6.0	7.0	7.8	8.2	9.0	10.4	12.0	13.0	15.2	16.4	18.2	21.4	23.0	28.6	40.8	61.4	124.8	5.6	6.6	7.0	11.2	15.0	35.8
AV.	6.1	7.0	7.8	8.2	9.05	10.4	12.0	12.9	15.05	16.5	18.3	21.5	22.8	28.6	40.6	61.4	126.2	5.6	6.6	7.1	11.3	14.9	36.1

TIMES OF DESCENT OF VARIOUS SIZES OF COAL AND SHALE THROUGH FORTY-EIGHT INCHES OF STILL WATER.

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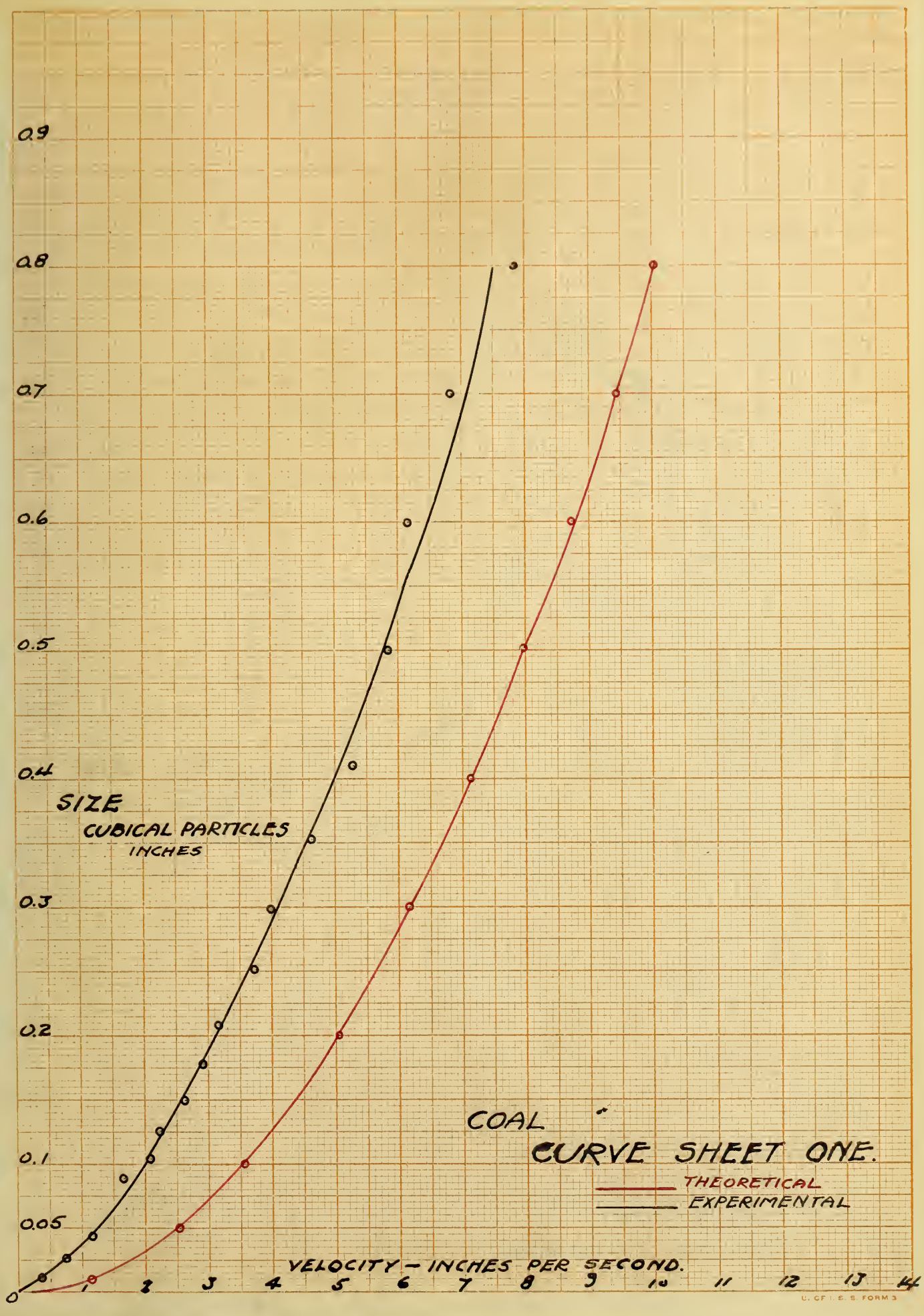

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VELOCITY — INCHES PER SECOND.
COAL
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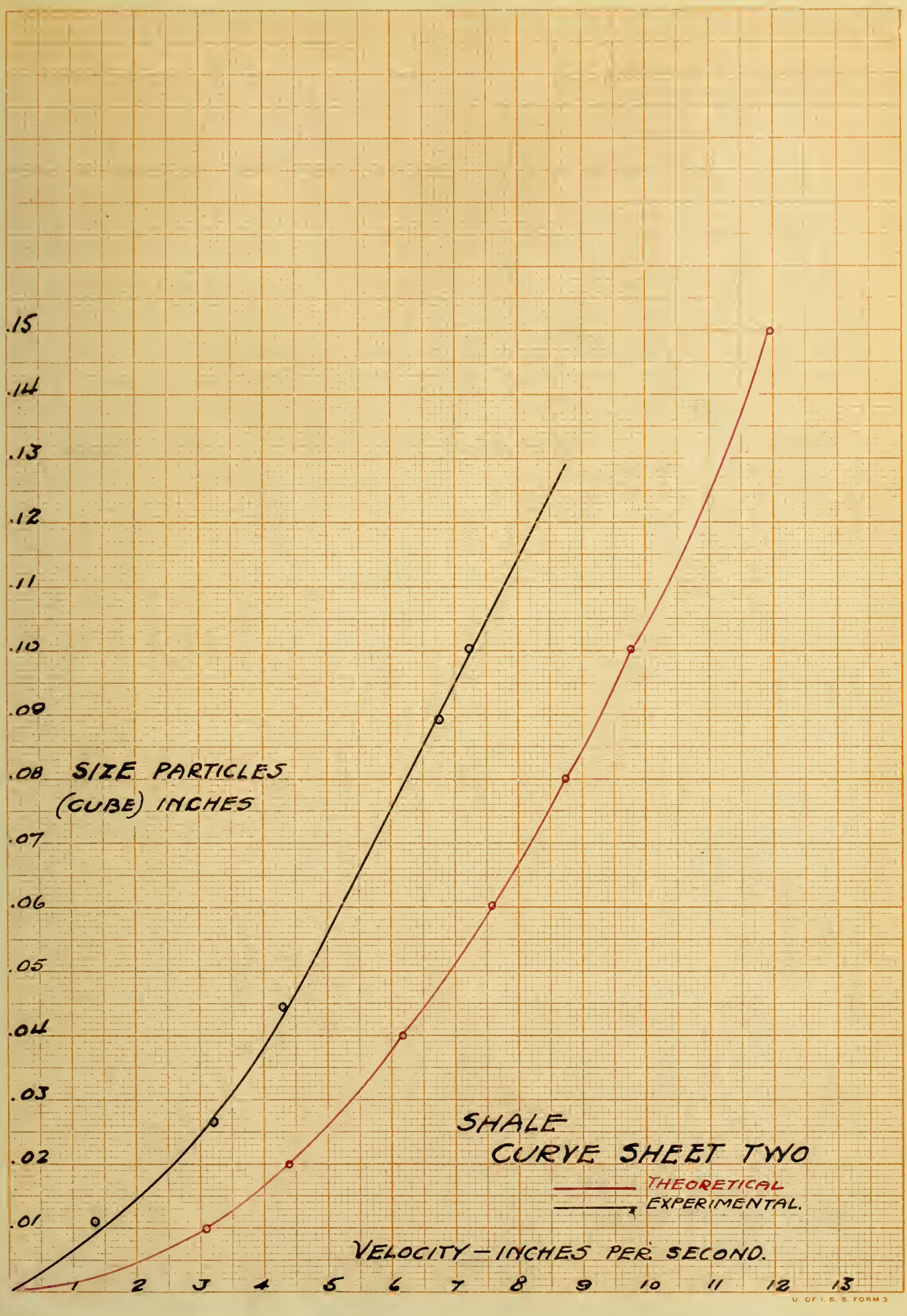

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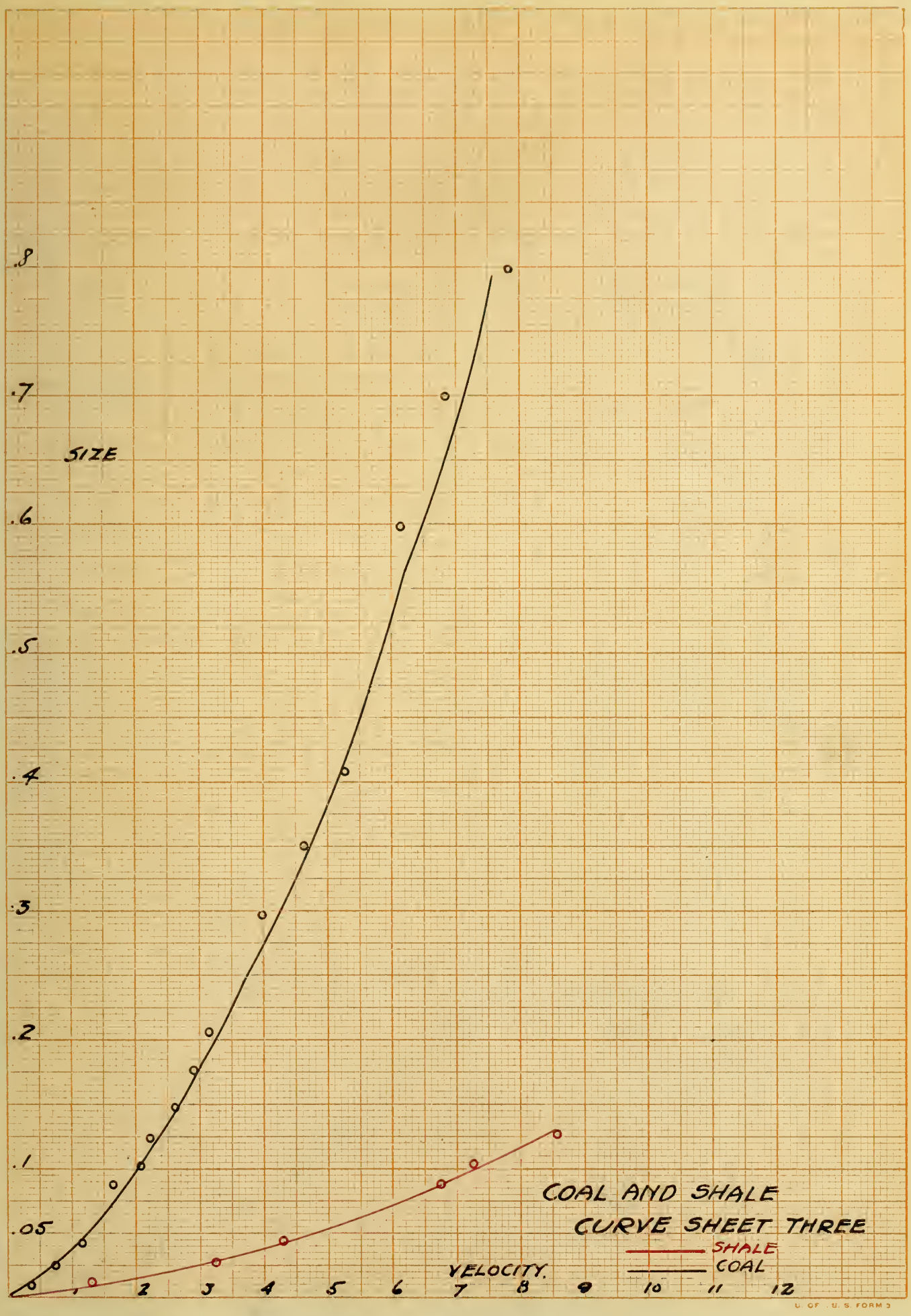
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VELOCITY.
COAL AND SHALE
CURVE SHEET THREE
SHALE
COAL

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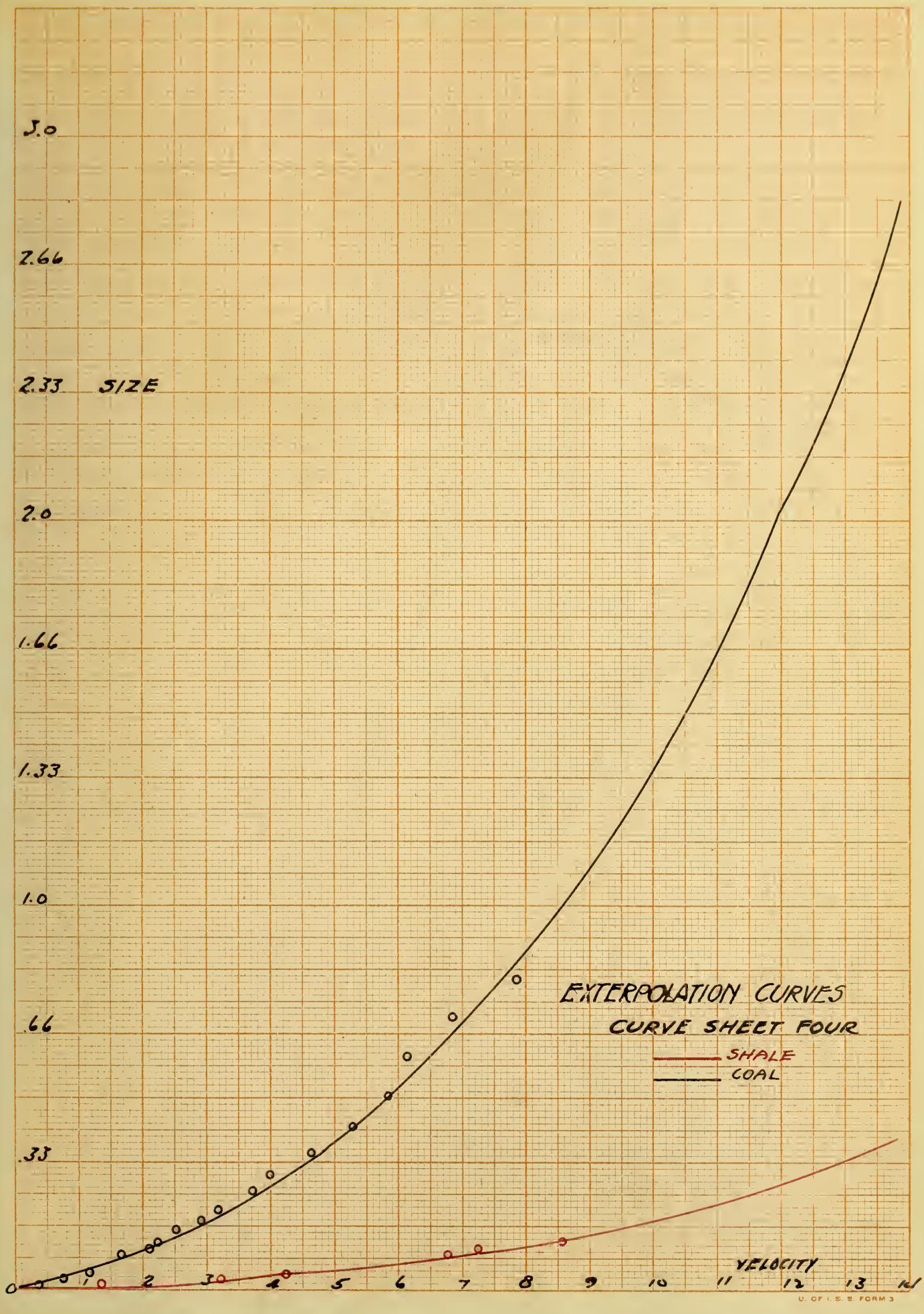

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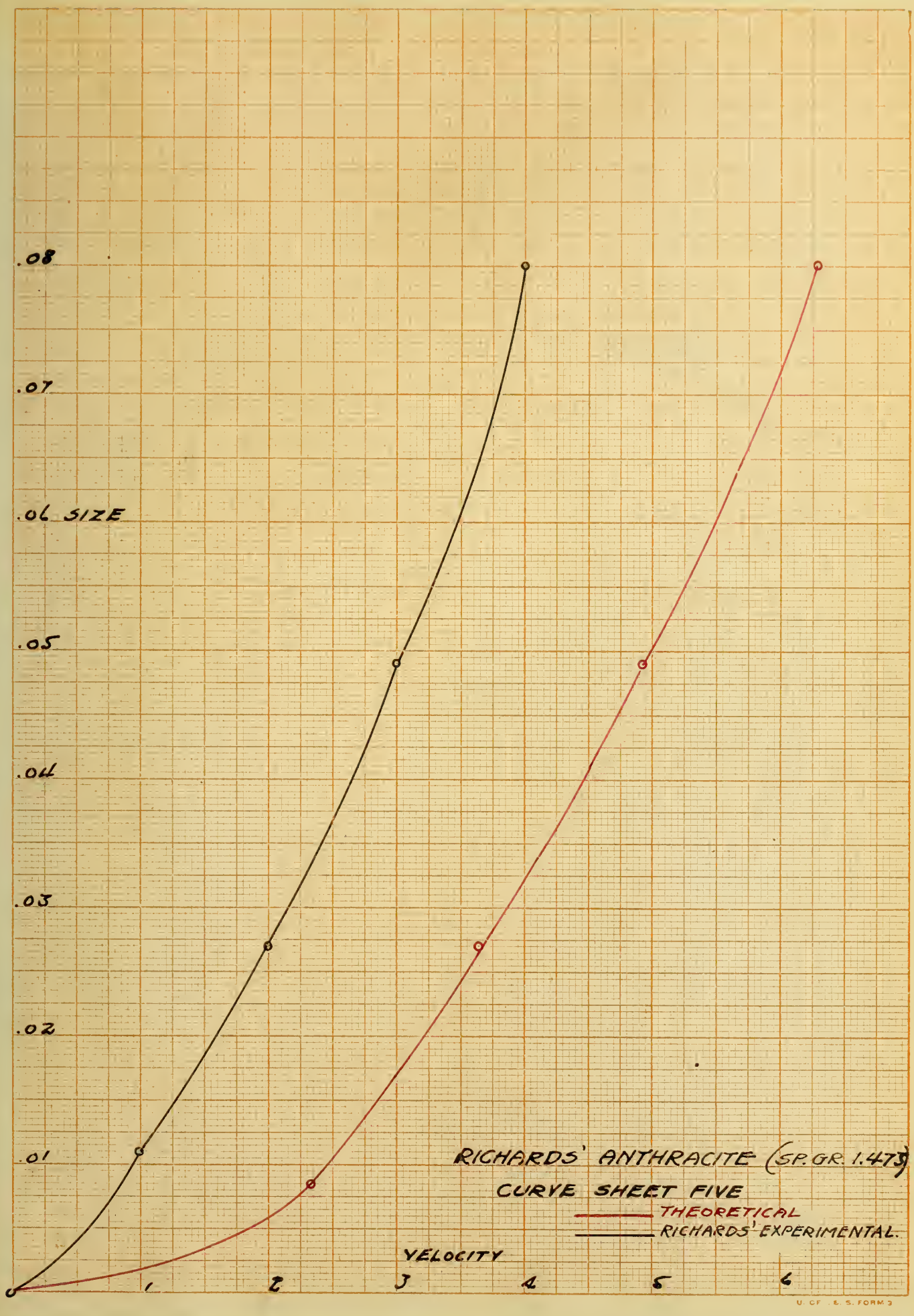

RICHARDS' ANTHRACITE (SP. GR. 1.473)

CURVE SHEET FIVE

THEORETICAL

RICHARDS' EXPERIMENTAL.

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